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Numerical and experimental study on the heat and mass transfer of porous plate water sublimator with constant heat flux boundary condition

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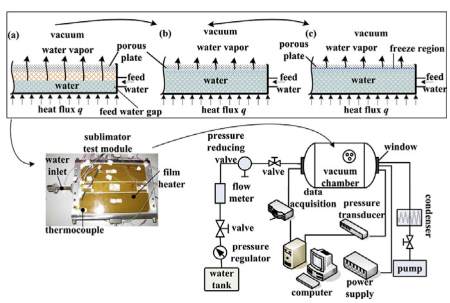
HIGHLIGHTS

- Mathematical model of porous plate water sublimator was presented.
- Numerical model was validated through experiment results.
- Pore scale phase change locations were obtained through numerical model.
- Evaporation/sublimation mass flow rate through the porous plate was estimated.

GRAPHICAL ABSTRACT



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ABSTRACT

Water sublimators offer effective heat rejection for the spacecraft, which work in warm environments or with peak heat loads, by evaporating or sublimating water into the vacuum. In this study, the heat and mass transfer of porous plate water sublimator with constant heat flux boundary condition was investigated numerically and experimentally. The startup process of sublimator was divided into three continuous states to analyze its work characteristics: water evaporation in the feed water gap state, water evaporation in the porous plate state and the alternation of evaporation and sublimation in the porous plate state. The locations of evaporation/sublimation front and freezing/thawing interface in the micron porous plate associate with the rarefied water vapor flow through the porous plate were taken into consideration. The heat and mass transfer equations coupling with phase change and rarefied gas flow through the porous plate were established and solved to evaluate the sublimator temperatures, water and vapor mass flow rates, locations of phase change interfaces. In addition, experiments of a water sublimator test module were conducted to validate the numerical model. The experimental results obtained were consistent with the simulation results.

1. Introduction

Water sublimator is a kind of phase change thermal control device, which takes advantage of the high latent heat of water and can reject spacecraft waste heat by evaporating/sublimating water to the vacuum environment [1]. It can be used as a supplemental heat sink of space radiator to help spacecraft handling peak heat

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loads [10], and can be exclusively used for spacecraft which working in warm environments, in which radiation heat rejection by radiator couldn't meet the need of the thermal control requirements of vehicles. The strong points such as simplicity, reliability, small volume, high efficiency, excellent work performance in zero gravity and with changing heat loads make sublimator very suitable for space use [1,10].

Over the past few decades, various applications and experiments of sublimators were reported, but few of the previous researches focused on the thermal modeling methods. Water sublimator has been successfully used in various spacecraft thermal control systems, such as Apollo Lunar Module (LM), Saturn 1-B, Saturn V and EMU Portable Life Support System (PLSS) of America and Russia/Soviet Union [2–6]. In recent years, researches and experiments about X-38 sublimator, Contamination Insensitive Sublimator (CIS), Sublimator Driven Coldplate (SDC) and Integrated Sublimator Driven Coldplate (ISDC) have been conducted by American researchers [7–12], due to the more critical thermal control requirements of the missions such as Altair LM and Orion Crew Module.

Among the above literatures, Hamilton Standard presented a steady state heat conduction analysis method to predict the steady state heat rejection ability of sublimator [2]. Rubik B. Sheth established a model of Sublimator Driven Coldplate (SDC) coupon through Thermal Desktop software and obtained the temperature distribution [8]. However, the detailed work performances and microscopic phase change processes of sublimator couldn't be revealed through these methods.

The basic issue of phase change processes with solidification, evaporation, thawing and sublimation taking place in porous mediums has been extensively studied in early investigations [14–25]. In particular, M.C. Olguín developed an analytical solution about the coupled problem of heat and mass transfer during the solidification of high-water content materials [14]. The authors also took into account the influence of material characteristics and process variables on the advance of the freezing and sublimation fronts, temperature and water vapor profiles and weight loss [14]. Y.C. Fey developed analytical solutions for the effect of convection heat transfer on the temperature, moisture concentration, pressure and sublimation front location in a sublimating frozen semi-infinite moist porous medium [15]. T. Lu numerically and experimentally studied the heat and mass transfer in paper drying [16], M. Leung theoretically studied the phase change problem about thawing of frozen food [17], F. He, Yuan-Qing Liu investigated transpiration cooling in porous mediums through experimental and numerical method respectively [18,19]. O. Rahli focused on the experimental analysis of transient-regime heat transfer with liquid–vapor phase change in a fluid as it flows through a porous medium composed of small bronze spheres [20]. To build a simple, engineering-approach simulation tool to define the HP characteristics of small HPs, C. Ferrandi described a lumped parameter numerical model which is able to simulate the transient as well as the steady-state operation of a sintered heat pipe [21].

It should be noted that, though some of the studies mentioned above deal with phase change problems with forced flow and some deal with process of freezing with sublimation, these processes are much different from the work process of sublimator. For instance, most of the processes take place in one kind of porous medium, and have specific work mode. But the work processes of water sublimator include the coupling of heat and mass transfer with forced flow, and the existence of one or two moving phase change interfaces (evaporation/sublimation front and freezing/thawing interface) in two different media (feed water gap and porous plate). Thus, the work modes of sublimator and locations of moving phase change interfaces are uncertain, furthermore, the flow mechanisms of water vapor flow through the porous plate is transformable according to different work modes. These factors make both the numerical and experimental study of sublimator even more difficult.

Visual design of test models and special observation techniques including photolithographic technique, high-speed video imaging system and X-ray microtomography have been conducted to evaluate the pore-scale phase change behaviors in porous structures [22–25]. In the case of sublimator, the work of sublimator requires vacuum environment, and phase changes are unexpected to occur on the surface of the porous medium. Therefore, it is almost impossible to observe the pore-scale phase change behaviors in experiments, using existing observation equipments. Parameters such as the evaporation/sublimation temperature of water/ice, locations of water-ice interface, sublimation/evaporation front and pore scale water movement inside the micron porous plate are also difficult to be measured.

Motivated by the facts discussed, we focus on the numerical investigation of the detailed work characteristic of water sublimator. Firstly, we divide the startup process of sublimator into three continuous states: water evaporation in the feed water gap state, water evaporation in the porous plate state and the alternation of evaporation and sublimation in the porous plate state. Then heat and mass transfer equations coupling with moving phase change interfaces are established and numerically solved. Dynamics of the parameters such as temperature, liquid and vapor mass flow rate and locations of phase change interfaces during the startup of sublimator with constant heat flux boundary condition are obtained. Finally, experimental results of the sublimator with the same thermal boundary conditions are presented to validate the model and numerical results.

2. Work mechanism of sublimator

The triple point pressure and temperature of water are approximately 610 Pa and 273.16 K respectively. The environmental pressure of spacecraft decreases to 10^{-4} Pa on a 200 km orbit and 10^{-11} Pa on a 3000 km orbit, which is far lower than the water triple point pressure. In such vacuum environment, water can change from solid phase to vapor phase directly. By absorbing of heat in water phase change processes, sublimator can reject spacecraft waste heat effectively and adjust itself to the heat load without active control and moving parts [1].

A simplified structure of a single module water sublimator with constant heat flux boundary is shown in Fig. 1. The sublimator is mainly composed of porous plate and feed water gap. The bottom wall of the feed water gap is heated with a constant heat flux q, the top of the feed water gap is covered by the porous plate. Water can be sent to the sublimator through the feed water inlet under feed water pressure, and change phase in the sequence as liquid phase → solid phase → vapor phase by aptly utilizing the vacuum environment. Water vapor produced by evaporation or ice sublimation vent to the outer space through the porous plate. To analyze the detailed work performance of sublimator, we divide the startup process of sublimator into three macroscopic stages discussed as follows.

(1). Water evaporates in feed water gap (Fig. 1(a)). If the sublimator is considered to startup, feed water is sent to the sublimator under a constant pressure. Once the feed water enters in the feed water gap, it is subjected to vacuum and turns to superheated water, and intensive evaporation will occur.

(2). Water evaporates in the porous plate state (Fig. 1(b)). If the feed water gap is filled full of water before the evaporation surface freeze, feed water will enter to the porous plate